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PERFORMANCE ENHANCEMENT OF A SOLAR AIR HEATER EQUIPPED WITH FLOW SEPARATORS – A CFD APPROACH

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ABSTRACT

Generally, it is found that solar air heaters are associated with lower conversion efficiencies because the heat carrying air medium has lower density. Many investigators have tried different design interventions to improve upon the efficiency of the collectors, especially by adopting different types of turbulence generating mechanisms. Nevertheless, enhancing the thermal effectiveness by means of forming turbulence along the vflow path is possible by using flow separating mechanisms. Flow separating geometries along the flow path such as circular, hexagonal and octagonal channels help in causing the desired turbulence to enhance convective heat transfer. These flow separators facilitate in breaking the viscous sub-layer because of the greater turbulence that they generate. Flow separators also generate a greater exchange of momentum among the air particles carrying heat. This study presents, enhanced convective heat transfer mechanism of the medium created due to the improved turbulence intensity. Circular shaped flow separators are found to provide a significant thermo-hydraulic enhancement factor while the octagonal shaped flow separators are capable of providing a greater thermal performance.

KEYWORDS: Flow Separators, Turbulence, Convective Heat Transfer & Solar Air Heaters

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Original Article

INTRODUCTION

Air heating for commercial and industrial application such as drying and space heating is now–a-days being done with the help of solar air heaters. These solar collectors suffer from a deficiency of lower thermal efficiency of the absorber plate because of the presence of laminar sub layer. It is therefore necessary to develop a mechanism to destroy the laminar sub layer and enhance the convective heat transfer by adopting new flow disturbing mechanisms such as flow path disturbing channels.

Deep et al. [1] numerically studied a solar air heater with ribs attached to the collector plate. They found that the thermo-hydraulic performance gets affected due to eddies being generated along the ribs installed on the collector plate. Sompol et al. [2] studied the influence of trapezoidal and rectangular winglet vortex generator on the performance characteristics of a solar collector, with and without pores. Their study showed that the heat transfer capability improved significantly when compared to that of smooth duct. The effect of spherical turbulators on thermodynamic enhancement factor and thermal performance of a solar air heater was investigated by Manjunath et al. [3]. The thermal efficiency was found to get augmented with enlargement in diameter of the sphere and decrease in roughness pitch.

Ali et al. [4] analyzed an air heater in which the air flows through a helical path. Their study found that the thermal efficiency of air heater with helical channeling and double pass was 14.7% greater than the smooth duct. Also, 8.6% higher thermal efficiency was observed for finned solar air heater having the same air discharge

compared to that of the smoother duct. Sharma et al. [5] in their work, have shown the effect of using flow obstacles in a solar air heater along the flow path and how these obstacles help in achieving a better convective heat transfer. Dongxu et al. [6] carried out CFD analysis of a solar air heater having V ribs in large numbers on the absorber plate of a solar collector for enhancement of thermal performance. Their investigation found that the multi V-shaped turbulators generated helical shaped vortex flows that facilitated the mixing of air between the warmer air next to the absorber plate and the colder air of the mainstream flow.

Mesut et al. [7] have studied the efficacy of an absorber plate having conical shape. The investigation found a remarkable enhancement in thermal performance for absorber plate with conical shape in comparison with a flat absorber plate. The study showed that the effectiveness of the air heater depended on range of Reynolds number, geometry of the collector and the incident radiation. Rajesh et al. [8] have investigated the influence of absorber plate attached with corrugated fins of herringbone shape. It was found from the study that the thermal performance of solar air heater with fins improved remarkably but at the expense of greater power to pump the air across the collector. Solar air heater with an arched shaped absorber plate carrying turbulators was investigated by Simarpreet et al [9]. It was noted from the study that the arched shape configuration of the collector significantly improved the thermal efficiency of the solar collector attached with turbulators of different designs. Manjunath et al. [10] numerically studied the influence of absorber plate with sinusoidal shaped on enhanced convective heat transfer capability and thermal enhancement factor for a wide range of mass flow rates. The effective thermal enhancement of the adopted corrugations was significant at lower Reynolds number range. Handoyo and Ischani [11] performed numerical and experimental studies on effect of spacing width of delta shaped obstacles in V corrugated channel SAH. The highest Nu number and friction factor were 94.2 and 0.628 at spacing to height ratio = 0.5 and was only 27.2 and 0.0316 at no obstacle. The model with spacing ratio of 1 was observed to be optimal with consideration of friction factor and efficiency.

It can be noted from the literature that flow disturbance caused using turbulators helps to augment the capability of heat transfer thereby breaking the viscus sub layer between the absorber plate and the flowing air. In this work, a numerical study is carried out to explore the effect of absorber duct flow path disturbance causing turbulence generators on the thermal efficiency and thermodynamic enhancement factor.

2. COLLECTOR CONFIGURATION

The solar collector configuration without turbulence generators called as the smooth duct is as shown in figure 1. The test section is made up of an absorber duct of length 1 m, width 0.2 m and height of 30 mm which is covered with a 0.5 mm thick copper absorber plate. The entrance and exit ducts are of 0.388 m and 0.194 m length respectively having the same cross section area as that of the absorber duct.

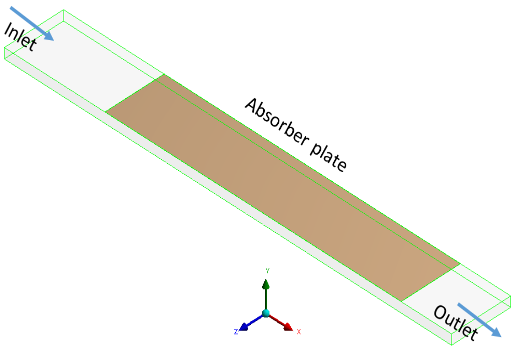

Figure 1: Base Model (Plain Duct) of the Solar Air Heater.

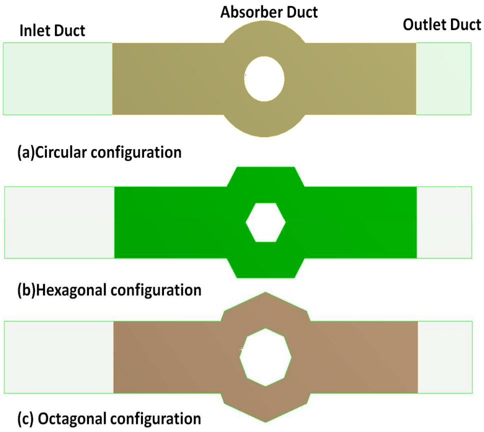

Figure 2: Plan View of Configuration with Flow Separators.

Figure 2(a) shows the plan view of the solar collector with circular flow separators. It can be observed that the flow path is equally divided into a diverging and converging flow passage. In figure 2(b) and (c), configurations with hexagonal and octagonal flow path separators are shown. All the configurations are made comparable as the heat flux due to solar radiation is kept constant.

3. DISCRETIZATION OF NUMERICAL MODEL

The numerical mesh generation of the collector is done using work-bench design modeler available under Ansys. To achieve grid independency of the numerical model, the analysis for the smooth duct configuration is performed by using different size of elements and is as given in table 1. It can be seen from this table that the variation in performance indicator, Nusselt number decreases as the size of elements become smaller. Elements size less than 3.5 mm having variation of Nusselt number below 0.25% is adopted for the remaining configurations. Figure 3 shows the localized views of some of the meshed domain.

Table 1: Mesh Independency Test Parameters

Mesh Size (mm)	Number of Elements	Nusselt Number (Nu)
4.5	465985	34.656
4	580552	36.563
3.5	795527	38.925
2.5	1685123	38.939
2	2869001	38.939

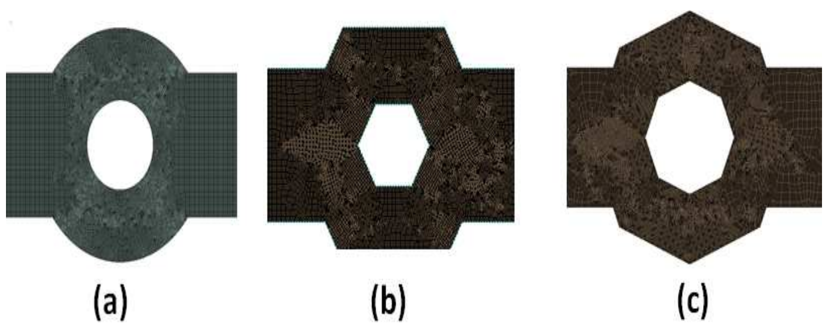

Figure 3: Localized View of the Meshed Domain (a) Circular Configuration, (b) Octagonal Configuration.

4. NUMERICAL FORMULATION

To solve the domain flow equations, boundary conditions as obtained from experimental studies are adopted. Corresponding to the inlet, a mass flow rate related to the flow Reynolds number is applied. At the outlet, a fully developed zero gradient outflow condition is applied. A solar irradiation is applied in the form of heat flux on the top surface of the absorber plate. At the interface region of wall and fluid region, a zero-slip condition is adopted. Pressure velocity coupling is done using SIMPLE algorithm is adopted. To solve the turbulence formulation, enhanced wall treatment and viscous heating available in RNG k-ε turbulence model is used. Second order upwind scheme is used for discretization purpose. The Fluent code available in Ansys is used to carry out the numerical simulation.

It is assumed that the thermo physical properties of the copper absorber plate do not change with temperature. Numerical analysis is carried out to solve governing partial differential conservation equations for the heat transfer and flow. The CFD formulations adopted in the study are based on the numerical scheme adopted by Manjunath et al. [10]. The equations of conservation are solved for the three-dimensional computation flow field, to develop the fields for temperature for the absorber plate and velocity, pressure and temperature fields for the fluid medium inside the collector. A residual of 1e-6 for convergence criteria is adopted for the continuity, velocities, energy and turbulence parameters.

5. VALIDATION OF THE NUMERICAL MODEL

Numerical Validation of the smooth duct model is carried out using Dittus-Boelter equation (1), [10]. Dittus-Boelter equation is given by

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \qquad (1)$$

The performance parameter chosen for base model validation study is Nusselt number. The values of Nusselt number procured from CFD study and that found from theoretical Dittus-Boelter equation are compared against various values of flow Reynolds number considered in the analysis. Figure 4 depicts the validation graph which compares the Nusselt numbers obtained from CFD analysis and Dittus-Boelter equation for various values Reynolds number considered in the analysis. It is noted that the numerical results are close to each other with that obtained from Dittus-Boelter equation.

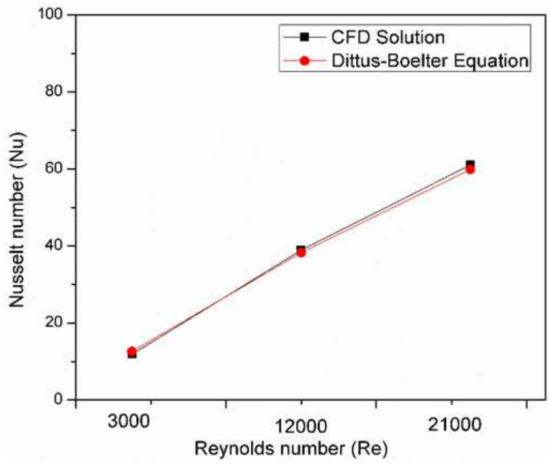

Figure 4: Validation Graph for Numerical Results with that of Dittus-Boelter Equation

6. RESULTS AND DISCUSSIONS

The circular, hexagonal and octagonal flow separators adopted in the solar air heater is numerically analyzed and is compared with that of the smooth duct configuration. In all these cases, identical boundary conditions are applied with Reynolds number ranging from 3K to 24K and heat flux of 910 W/m^2. The heat flux applied is the average value of solar radiation between 11 a.m. to 1 p.m. as recorded at local ambience under fair weather conditions with a sun shine factor of 0.85. The performance parameters adopted in the study are absorber plate temperature coefficientC_{AT}, Nusselt number 'Nu', Friction factor ratio 'f/f_s', heat transfer coefficient 'h' and Thermo-hydraulic enhancement factor 'THEF'. The turbulence of the flow is measured in terms of turbulence viscosity ratio 'TVR'.

The absorber plate temperature coefficient C_{AT} is the non-dimensionalized form of absorber plate temperature and is given in eq(2). The Thermodynamic enhancement factor 'THEF' is given in eq(3).

$$C_{AT} = \left(T - T_a\right) / T_a \tag{2}$$

$$THEF = \left(Nu / Nu_s\right) / \left(f \;/\; f_s \right) \tag{3}$$

6.1 Thermal Performance

The thermal performance of the air heater is mainly quantified in terms of Nusselt number of the flow. The plot of Nusselt number for various configurations along with the base model against flow Reynolds number is shown in figure 5. It is discernable from this graph, that, the Nusselt number is significantly higher for octagonal configuration compared to that of hexagonal and circular configurations. The octagonal flow obstruction in the center of the absorber duct and the matching side walls help in the flow separation leading to greater turbulence generated in the flow domain compared to other configurations. The number of sharp edges in these geometries is also greater in the octagonal configuration. These sharp edges cause flow separations and flow reattachments along the side walls. The turbulence that helps the enhancement of convective heat transfer is quantified in terms of turbulent viscosity ratio (TVR) and is as shown in figure 6. Figure 7 shows the contour plot for turbulent viscosity ratio for the 4 configurations. It can be observed from these plots that the octagonal configuration generates greater turbulence towards the downstream end of the central obstruction and their matching side walls. Also there is a greater disturbance towards the convergence section of the flow and thus causing better convective heat transfer to the flowing air.

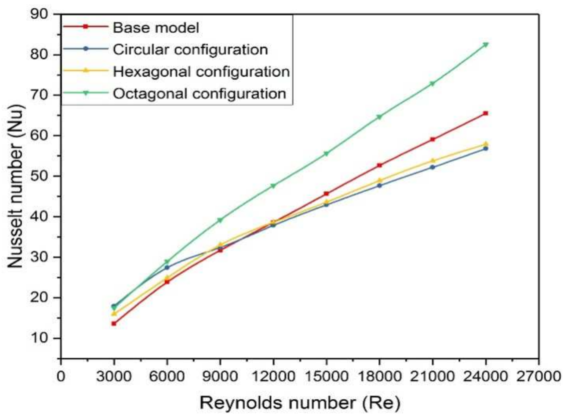

Figure 5: Plot of Nusselt Number against Reynolds Number.

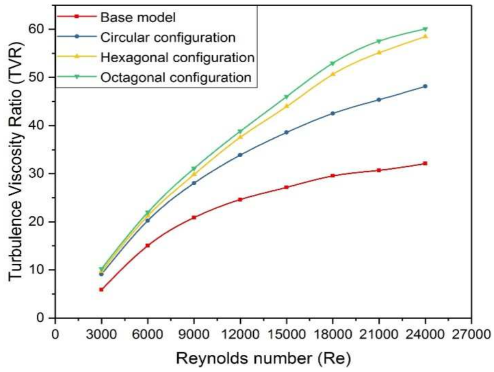

Figure 6: Plot of Turbulent Viscosity Ratio (TVR) Versus Reynolds Number.

The better enhancement in Nusselt number is further justified from the plot of absorber plate temperature coefficient (C_{AT}) which shows a lower absorber plate temperature for the octagonal configuration followed by hexagonal and circular configurations (figure 8). This is majorly because of the fact that with enhancement in convective heat transfer, the absorber plate gets cooled faster than that of the ones with lesser Nusselt number. Figure 9 shows the absorber plate temperature plot for the 4 configurations and it can be seen from these plots that the absorber plate temperature is significantly lower than the other configurations.

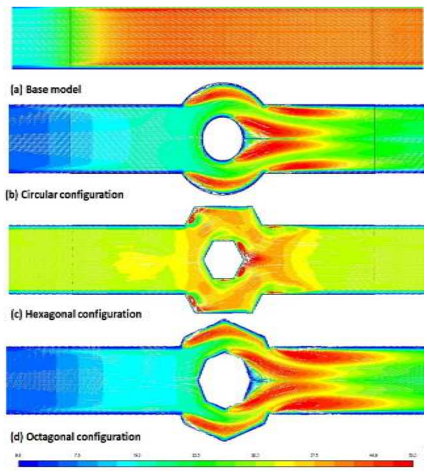

Figure 7: Contour Plot of Turbulent Viscosity Ratio for Configurations Used.

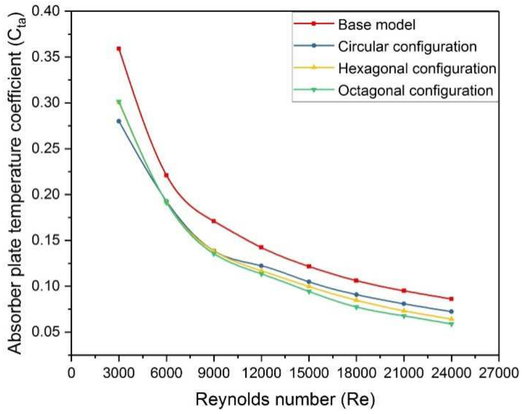

Figure 8: Plot of Temperature Coefficient versus Reynolds Number for the Absorber Plate.

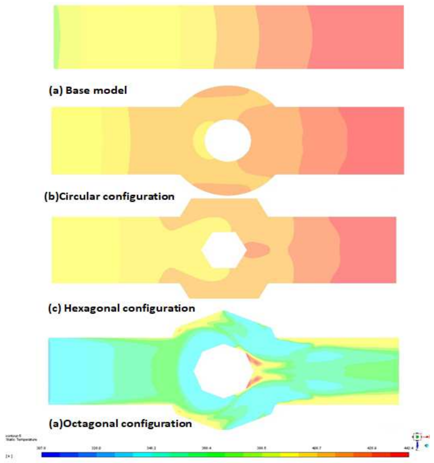

Figure 9: Contour Plot of Absorber Plate Temperature for Different Configurations.

6.2. Thermo Hydraulic Performance

Figure 9 shows the contour plot for the 3 configurations. The absorber plate for octagonal configuration shows a lower temperature profile indicating a cooler absorber plate due to a better heat transfer taking place inside the duct. However, for other configurations, the absorber plate temperature is higher towards the downstream end indicating a lower heat transfer of the collector.

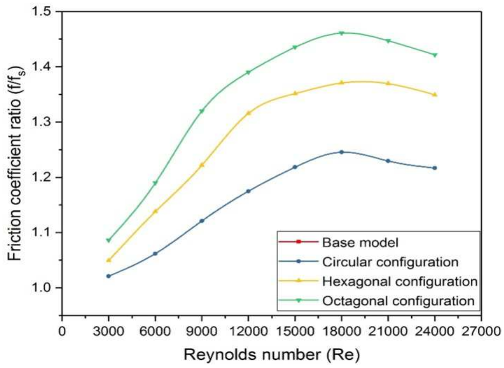

Figure 10: Plot of Friction Factor Ratio with Reynolds Number.

With greater turbulence inducement in the octagonal configuration, the pressure drop across the duct also increases significantly. As shown in figure 10. The friction factor ratio (f/f_s) plot (figure 11) is the ratio of friction coefficient with respect to the smooth duct. It is seen from figure 11, that, the friction ratio increases significantly up to 18000 Re and then marginally drops further. The friction ratio is the highest for octagonal configuration and smaller for circular configuration. The resistance to flow increases with more edges on the obstacle and the side wall of the flow path and hence demands a greater energy to move the air across the duct.

The thermo-hydraulic enhancement factor (THEF) is plotted with respect to Reynolds number as shown in figure 11. Since this factor takes into account the pumping power in terms of friction factor, it indicates a contrasting trend compared to that of thermal performance. The THEF is greater than one for circular configuration up to a Rebuilds number of 9000. Also, the THEF is marginally lower for octagonal configuration and is the lowest for hexagonal configuration.

This is due to the fact that, the higher friction loss, that takes place while pushing the air through the duct, reduces the overall performance even though the thermal performance is better for octagonal configuration. The velocity contour plot corresponding to 3000 Re and 21000 Re for the three configurations are shown in figure 12. It can be noted from these plots that the flow towards the downstream end of the central obstruction is stalled and the stalling is greater at higher Reynolds numbers. It is these stalling that causes greater pressure drop across the duct and will demand greater pumping power. Also, it can be observed, that, for Octagonal configuration, vortices are generated on the side walls and is absent when the mass flow rate is lower.

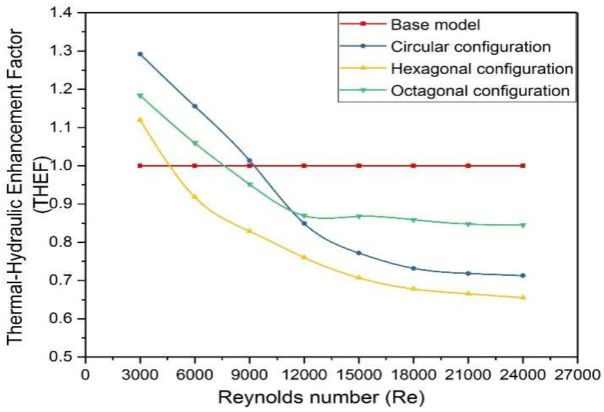

Figure 11: Plot of Thermo-hydraulic Enhancement Factor with Reynolds Number.

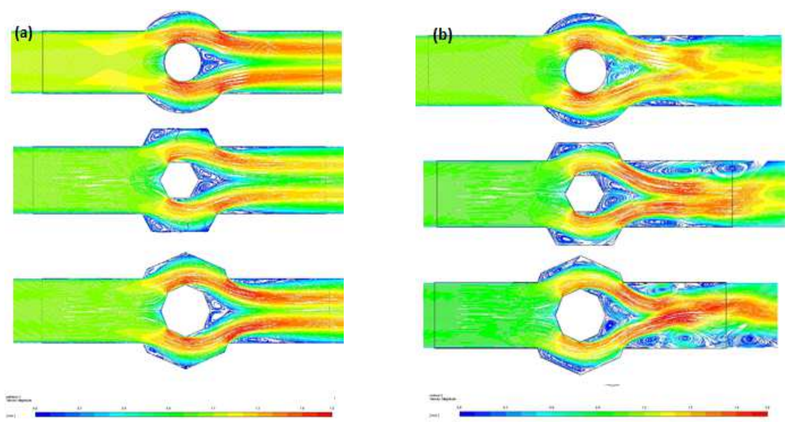

Figure 12: Velocity Path Line Plot (a) Re = 3000 (b) Re = 21000.

7. CONCLUSIONS

The numerical study of a solar air heater with flow separations are carried out and the following conclusions are drawn from the study.

- The circular, hexagonal and octagonal flow separators in general enhance the thermal efficiency as well as thermo-hydraulic enhancement factor (THEF) for the collector at lower range of Reynolds number.
- The octagonal shaped flow separators provide the highest thermal enhancement in terms of Nusselt number compared to that of circular and hexagonal shaped flow separators.

- The thermo-hydraulic enhancement factor (THEF) is the highest for configuration with circular flow separators due to marginal pressure loss compared to the other configurations which demand more pumping power.
- The best operating range for the collector is between 3000 to 9000 Reynolds numbers.

8. ACKNOWLEDGEMENTS

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REFERENCES

1. *Deep Singh T., Mohd. K. K, Manabendra P., Performance evaluation of solar air heater with novel hyperbolic rib geometry, Renewable Energy 105 (2017) 786e797.*
2. *Sompol S., Pitak P., Pongjet Promvonge, C. Thianpong, Monsak P., Thermal performance in solar air heater with perforated-winglet-type vortex generator, Solar Energy 170 (2018) 1101–1117.*
3. *Owaid, A. I., Tariq, M., Issa, H., Sabeeh, H., & Ali, M. The heat losses experimentally in the evacuated tubes solar collector system in Baghdad-Iraq Climate.*
4. *Manjunath M. S., Karanth K. V. Sharma N. Y., Numerical analysis of the influence of spherical turbulence generators on heat transfer enhancement of flat plate solar air heater, Energy, 121 (2017) 616-630.*
5. *Ali H. Mehrdad M., Experimental analysis and numerical modeling of solar air heater with helical flow path, Solar Energy 162 (2018) 278–288.*
6. *Ahire, Y. M., Hamoud, A. A., & Ghadle, K. P. Analysis of thermal stresses in thin circular plate due to moving heat source.*
7. *N Yagnesh Sharma, Madhwesh N, K Vasudeva Karanth,, "The effect of flow obstacles of different shapes for generating turbulent flow for improved performance of the solar air heater", Procedia Manufacturing 35 (2019) 1096–1101.*
8. *Dongxu J., Manman Z., Ping W., Shasha X., Numerical investigation of heat transfer and fluid flow in a solar air heater duct with multi V-shaped ribs on the absorber plate Energy 89 (2015) 178e190.*
9. *Mesut Abuska, Energy and exergy analysis of solar air heater having new design absorber plate with conical surface, Applied Thermal Engineering 131 (2018) 115–124.*
10. *Rajesh Kumar, Prabha Chand, Performance enhancement of solar air heater using herringbone corrugated fins, Energy 127 (2017) 271-279.*
11. *Bodade, P. R., Jogi, N., Gorde, M., Paropte, R., & Waghchore, R. Use of internal threads of different pitches to enhance heat transfer in a circular channel.*
12. *[9] Simarpreet Singh, Performance evaluation of a novel solar air heater with arched absorber plate, Renewable Energy 114 (2017) 879-886.*
13. *Manjunath M. S., Karanth K. V., Sharma N. Y., Numerical investigation on heat transfer enhancement of solar air heater using sinusoidal corrugations on absorber plate, International Journal of Mechanical Sciences 138–139 (2018) 219–228.*
14. *Sankar, A. R., Gunakala, S. R., & Comissiong, D. M. The effect of heat transfer on two-layered blood flow through a composite stenosis in the presence of a magnetic field.*
15. *Handoyo, E. A. and Ichsani, D. 'ScienceDirect Numerical studies on the effect of delta-shaped obstacles' spacing on the heat transfer and pressure drop in v-corrugated channel of solar air heater', Solar Energy, 2016, vol. 131, pp. 47–60.*

NOMENCLATURE

T	Temperature (K)
T_a	Ambient temperature (K)
Nu	Nusselt number
h	convective heat transfer coefficient (W/m^2K)
f	Friction factor

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